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SIMULATION OF A PROGRAMMED FREQUENCY SHIFT NEAR EXTRACTION FROM THE FERMILAB BOOSTER

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Abstract

The longitudinal phase space program ESME has been used to simulate the effects of a linear shift in RF frequency away from that appropriate for the accelerator guide field. This shift takes place in the new Booster low level RF and is used to position the particle bunches in Main Ring buckets in a reproducible fashion. Shifts in frequency are found to generate synchrotron oscillations; however the simulations show that these can be reduced to acceptable levels by introduction of jumps in RF phase preceeding the programmed frequency changes. Lowering the RF voltage near extraction from the Booster, a desirable operational feature, has also been investigated.

Introduction

The simulation program ESME[1] has been used to study a variety of phenomena in the Fermilab 8 GeV Booster accelerator. In this paper results are presented of simulations of a programmed shift in RF frequency away from that necessary to maintain synchronization with the magnetic guide field. This shift occurs near extraction from the Booster and is required as part of the process of phase locking the particle motion with the RF system of the Main Ring, the destination of most Booster beam. A frequency shift of this type has recently been implemented as part of a Booster RF upgrade.

In this paper are presented the details of the motivation for such a frequency shift and some of the simulation results obtained. In the Appendix is discussed how ESME was utilized to carry out this study.

Motivation

The cascade of accelerators at Fermilab consists of a 200 MeV Linac, an 8 GeV Booster, the Main Ring currently operating at energies up to 150 GeV, and the Tevatron with a top energy of 900 GeV. The Booster at injection forms the bunch structure which is maintained in the Main Ring and Tevatron. During its acceleration cycle the RF frequency, which varies from 30 MHz to 52.8 MHz as the beam energy increases, is controlled by an internal system. Radial position feedback is also used for RF phases. However at extraction the RF is governed by a reference oscillator and is phase and frequency locked to the Main Ring. Without such phase locking the beam is not regularly deposited into Main Ring accelerating buckets, so that intensity is unstable and beam loss high in that machine. The locking problem is compounded by the operation of the Booster itself. It is a rapid cycling (15 Hz) machine whose magnetic guide field is ramped in an analog manner using resonant circuit techniques. One effect of this is that there is some variation in the peak field, and thus RF frequency and phase at extraction.

Until recently the required locking was accomplished by arcane circuitry in which shifts of RF phase were applied with a variety of time constants. The undesirable feature of this system was that when activated ~2ms before extraction, it did not always respond well to the varying Booster conditions, and often resulted in abrupt phase shifts which led ultimately to degraded beam quality. The more modern system adjusts the RF phase in a smooth programmed fashion from its value under internal control to the appropriate Main Ring phase locked one. The studies described here assume that a frequency shift of 5 KHz on the 52.8 MHz signal is needed, and that this shift occurs over a time span of 2ms. The shifts occurring in practice are thought in general to be of this order or smaller.

Two versions of the system have been built and tested. In the first the frequency shift is totally decoupled from the normal Booster curve and moves linearly from its initial to its final value. In the second version the shift is applied but with time dependent shape similar to that of internal Booster control. The latter method is preferable as it leads to smaller deviations from normal synchronous operation.

Both types of programmed control have been simulated in this study. The specific frequency curves generated are shown in Figure 1, which presents the (zero suppressed) forms over the last 3ms of the accelerating cycle. For the first 1ms only internal control is active, and then the various shifts are applied for the last 2ms. For case (a) no shift is applied; this curve is shown only for comparison. Cases (b) and (c) represent positive and negative linear shifts reaching 5 KHz, while cases (d) and (e) represent shifts which are offsetted from case (a). As (c) and (d) represent the forms closer to current operation, most results presented below relate to them.

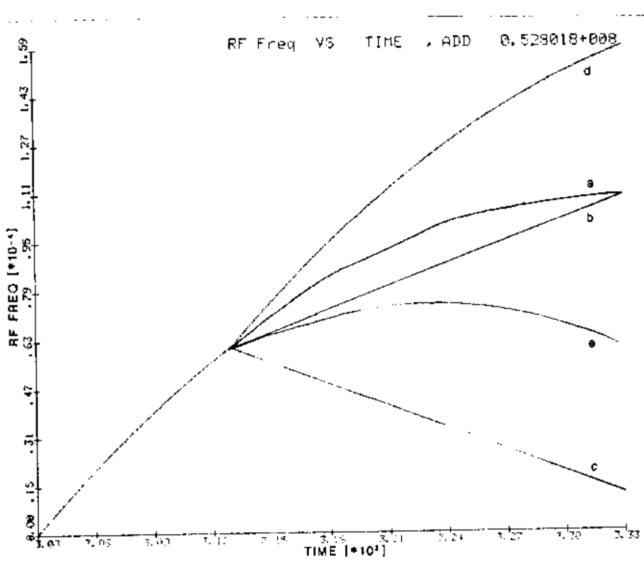

Figure 1. Frequency curves as functions of time. Curve (a) represents normal operation without frequency shifts. Curves (b)-(e) represent the various shifts described in the text.

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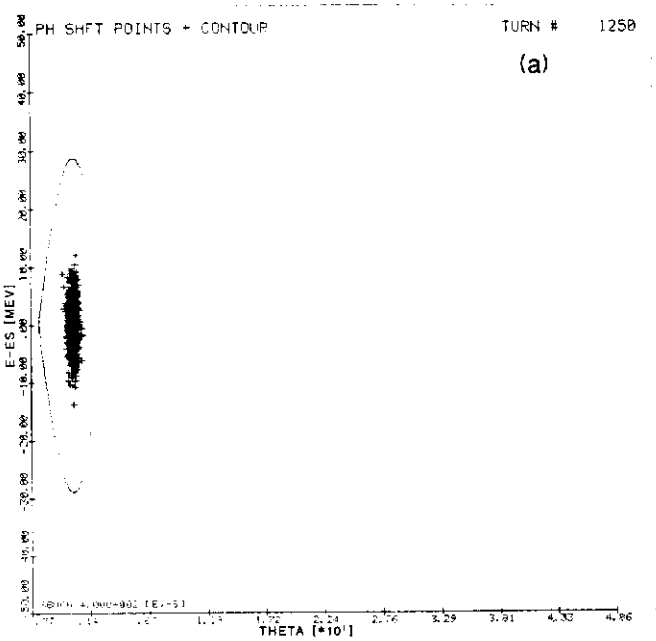

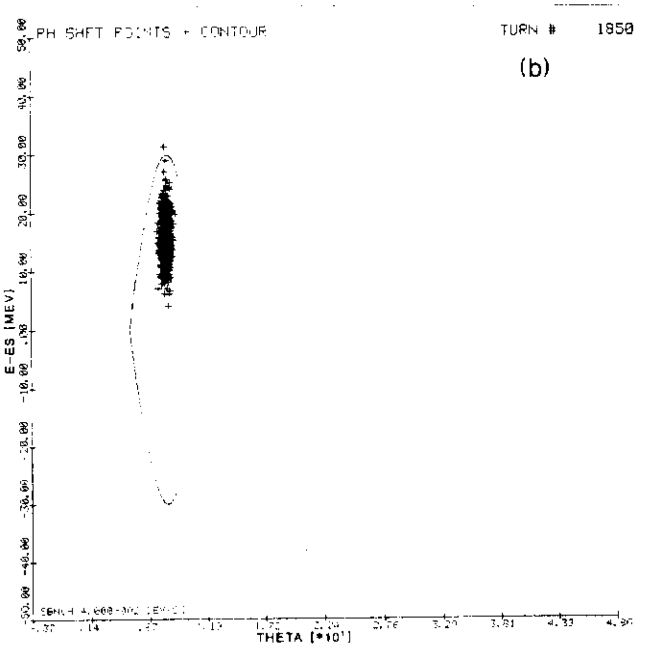

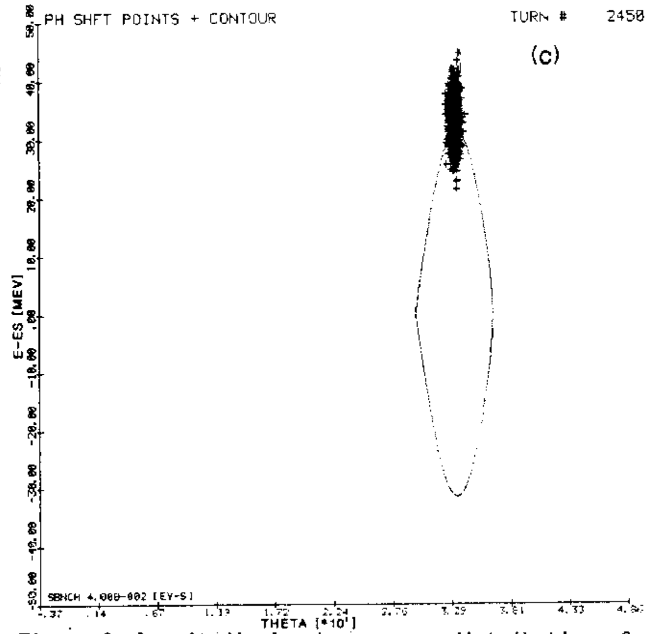

Figure 2. Longitudinal phase space distributions for the case of a frequency shift which tracks the synchronous frequency but deviates below it. Part a of the figure is just as the shift begins, part b is when the shift is half completed, and part c is at extraction when the shift has reached 5 KHz. The dotted curves in the figure represent the RF buckets, as calculated by standard techniques.

Simulation Results

Shown in Figure 2a is the distribution in longitudinal phase space for the single bunch of particles used in this tracking study. The horizontal axis represents the positions at a time when a particle synchronous with the guide field crosses the value zero. The vertical is the energy difference for each particle from such a synchronous one. The distribution used corresponds to a longitudinal emittance of .04 eV-sec (95%), the approximate value in the Booster after transition. For comparison, the curve shown in the figure is the RF bucket. The distribution given is at the time when the frequency shift begins. In part b of the figure is shown the phase space distribution in the middle of the procedure and in part c at extraction. The first point to note in examination of these data is that the phase shift, resulting from integration of the frequency, is not small, and for the parameters being used amounts at extraction to five full buckets. It is also clear that the particles move away from the synchronous energy, finally reaching a 35 MeV offset. A third point is that they are maintaining their phase stability, while appearing to leave the accelerating bucket. This effect is a subtle artifact of the program. It has been noted in the course if this work that many of the standard techniques for performing calculations in synchrotrons - such as determination of the bucket boundary - do not lead to correct results when phase shifts are applied.

One question posed of this simulation involves phase stability. The data of Figure 2 show that, for the parameters considered, the particles stay tightly bunched. A numerical measure of this fact is that the longitudinal emittance grows by only .1% as a result of the frequency shift. Simulations in which the shifts are increased by an order of magnitude, or in which the same shift is applied but over a considerably shorter period of time, have resulted in failure. Namely the inertia of the beam prevents it from responding to the frequency changes, with resulting emittance growth and particle loss.

It is a well known effect that an RF frequency change will correspond to a calculable change in effective radius of the particle motion. The mean radius shift from nominal is shown as a function of time in Figure 3a; the increase seen corresponds to the decreasing frequency case, and the magnitude is as calculated. Note however that the change is not accomplished without the introduction of synchrotron oscillations. Similar oscillations are seen in examination of mean energy or longitudinal position as functions of time. It was hypothesized by one of us (Q.K.) that it would be possible to

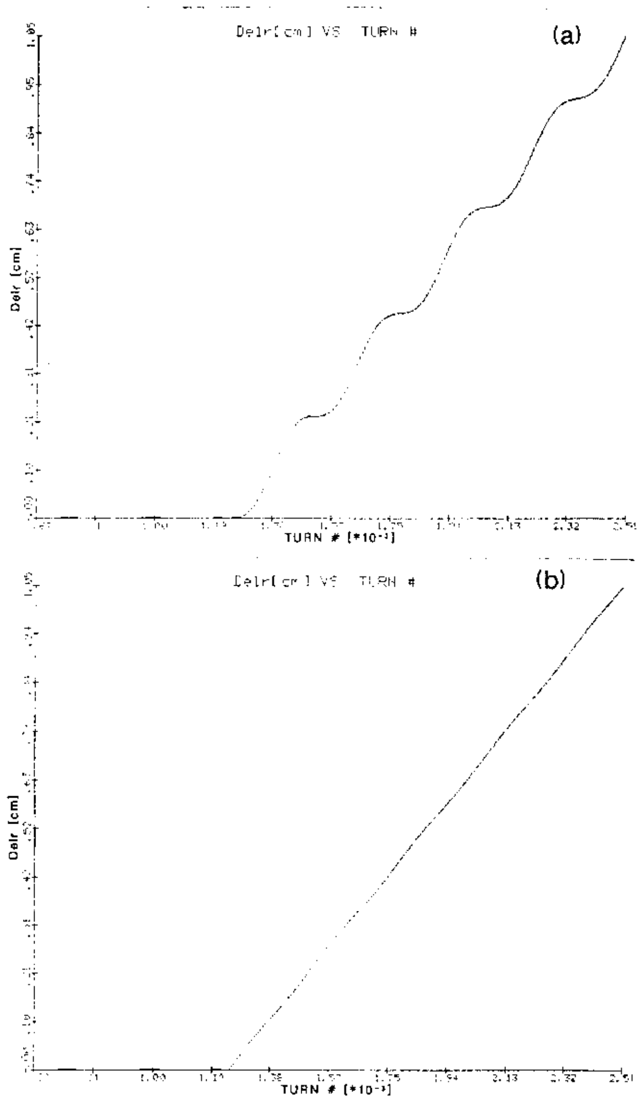

Figure 3. Offsets of the mean particle radius from the nominal machine value. In part a of the figure a frequency shift alone is imposed, in part b a 75 mr phase jump is applied to the RF before the frequency shift.

remove these oscillations by introduction of a phase jump immediately before the smooth frequency shift. Figure 3b shows that with an appropriately chosen jump this is indeed the case. The jump used to produce the curve is +75 mr of RF phase. For the case of frequency increases, and radius decreases, a value of -75 mr is found to be similarly successful.

One problem with the previous phase locking system was that, due to the large phase excursions which were occurring, it was necessary to employ a high RF voltage at extraction in order to maintain sufficient bucket area to contain the beam. The resulting bunches were not appropriately matched to the Main Ring buckets, and longitudinal emittance dilution resulted. A final goal of these studies has been to estimate the extent to which the voltage can be lowered with the new system. The results of the study are that a voltage reduced from the normal operating point at extraction of 340 KV to a value of 250 KV is not a problem, but that attempts to reach the desirable value of 100 KV lead to bunch shape distortion and emittance growth. The value achieved in practice[2] is about 230 KV, but is intensity dependent.

Conclusions

The new Booster phase lock system near extraction, involving programmed frequency shifts in the last 2ms of the cycle, has been studied in simulation. The studies show that for reasonable frequency shifts it is possible to maintain the phase stability of the beam. To cancel synchrotron oscillations it is necessary to insert an appropriate phase jump before the frequency shift. The results predict that it should be possible to lower somewhat the RF voltage at extraction.

Appendix

A brief presentation is given of how ESME has been run to produce the results presented. Some of what is described has been coded specifically for this project.

The voltage seen by a particle on a given turn is:

$$V = V_{max} \sin(h\theta + \phi)$$

where Vmax is the RF amplitude, h is the harmonic number, Θ is the angular position as described in the text, and ϕ is a phase offset. This offset is normally determined such as to maintain synchronization of the particles with the guide field (synchronous phase). However specification may also be given that ϕ change linearly, leading to a constant frequency offset, or quadratically, leading to a linear frequency shift. These applied phase offsets may be added to the normal synchronous phase or they may replace it entirely. This latter method is used to decouple the RF frequency from the guide field. However another action must be taken as well to complete the decoupling. The term $h\Theta$ in the phase is written with the assumption that the harmonic number h always represents the ratio of RF to particle revolution frequency. In the decoupled case h must represent that ratio at the time of decoupling, but is not proper as the revolution period changes. The desired result can be obtained by adding to the phase ϕ an additional term ψ, given by:

$$\psi_1 = 0$$

$$\psi_{n+1} = \pm[\psi_n + 2\pi h(\tau_n/\tau_1 - 1)]$$

where the plus sign applies below transition energy and the minus sign above, τ is the revolution period, and n is a turn counter.

The frequencies plotted by the program are calculated by determining the turn to turn phase change,

$$\Delta\phi = \phi_{n+1} - \phi_n$$

placing the result in the range,

$$-\pi < \Delta\phi < \pi$$

by addition or subtraction of 2π if necessary, and computing:

$$f_{n+1} = (h + 2\pi\,\Delta\phi)/\tau_{n+1}$$

References

1. J.A. MacLachlan, this conference, Paper L28

2. S. Holmes, Private communication